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Progress in High Temperature Speckle-Shift Strain Measurement System

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Progress In High Temperature Speckle - Shift Strain Measurement System

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ABSTRACT

A fast, easy to use speckle tracking system is under development for the speckle-shift strain measurement technique. Preliminary correlation tests on wire specimens show strong correlations of well developed speckle patterns. Stable cross-correlations were obtained from a tungsten filament at 2,480°C. An analysis of the optical system determines the minimum required sampling frequency of the speckle pattern to be 2.55 pixels per speckle.

INTRODUCTION

The Instrumentation and Control Technology Division of the Lewis Research Center has been developing an in-house capability to make one- and two-dimensional optical strain measurements on high temperature test specimens. The measurements are based on the speckle shift technique of I. Yamaguchi.[1] The first phase of this effort demonstrated one-dimensional strain measurements at temperatures up to 450° Celsius, with a resolution of 18 $\mu\epsilon$.[2] The Phase II effort expanded the Phase I system to provide a two-dimensional strain measurement capability. The Phase II system demonstrated one-dimensional and two-dimensional strain measurements at temperatures beyond 750°C with a resolution of 15 $\mu\epsilon$.[3]

The development of composite materials for use in high temperature applications extended the interest in the speckle-shift technique to strain measurements on small diameter fibers and wires of various compositions. This paper will cover the results of preliminary speckle correlation tests on wire and fiber specimens, and describe the Advanced System currently under development. Some of these results are described in more detail in the final report in the reference.[4]

Past implementations of the technique used a linear photodiode array to detect objective speckle reflected from a point on a diffuse test surface. Shifts of this speckle pattern are proportional to surface strain along the incident plane of the optical system. A feature of the speckle shift technique is its ability to automatically cancel many problematic terms of rigid body motion. However, excessive rigid body motions can move the reference speckle pattern off the one-dimensional detector, terminating the measurement. The advanced system now under development will address two practical limitations encountered in previous testing:

- Decorrelation errors due to off-axis rigid body motion shifts restrict the magnitude of specimen movements. The speckle-shift technique could be applied to more diverse test situations, such as component testing, if the specimen mounting and loading requirements were not rigorous.
- The low sampling rate of the strain measurements, on the order of 0.1 Hz, limits the response time of the system. Higher sampling rates would allow continuous loading at higher strain rates.

The use of a two-dimensional charge-coupled device (CCD) for the detector will reduce decorrelation errors due to rigid body motions. At the same time, a high speed image processing system is intended to increase the performance of the strain calculations to provide real time results.

THEORY

The laser speckle patterns, generated by the spatially coherent illumination of a rough specimen surface, shift when the surface is strained or when the specimen undergoes rigid body motion. The speckle patterns are recorded on a sensor array, and cross-correlations of the patterns before and after they move are calculated to determine the amount of shift between them. A dual beam measurement allows automatic cancellation of most terms of rigid body motion. By taking the difference in shifts of speckle patterns generated by two laser beams incident on the specimen from equal but opposite angles, error terms due to rigid body motion can be cancelled.

The geometry of the optical setup and careful alignment of the specimen limit the speckle shifts to an axis parallel to the sensitive axis of the measurement system, namely, the incident plane of the laser beams; the speckle patterns remain correlated as long as they do not shift along the transverse direction, off the linear photodiode array. Increasing the height (transverse integration distance) of the linear array reduces the chances of decorrelation, but not enough to eliminate transverse shift considerations from the design of the test system.

The current system will allow one-dimensional strain to be measured at a rate near the data acquisition rate, on diverse specimens, by providing a two-dimensional digital signal processor (DSP) based speckle tracking processor. Rigid body motion constraints and decorrelation events will be reduced by using a two-dimensional CCD array to record an extended speckle pattern. A two-dimensional speckle pattern will allow off-axis speckle shifts to be tracked dynamically.

Figure 1 shows the simplified geometry of the coordinate system. The specimen is in the lowercase x,y plane, and the sensor is defined to lie in the uppercase X,Y plane. The x,y and X,Y planes are separated by a distance L_0 along the z axis. Two-dimensional deformation of object points on the specimen are described by vector **a**(x,y), and the resulting shifts of the speckle pattern are given by vector A(X,Y). The shaded rectangle in the figure indicates a one-dimensional reference slice of the speckle pattern (one line of the 2-D CCD array) shifted from the origin by A(X,Y). The x,z plane is the plane of the incident laser beam, which comes from source point L_S.

After rigid body motion terms are cancelled out of the simplified speckle-shift equations, the surface strain ϵ_{xx} in the x direction can be calculated by the relation

$$\epsilon_{xx} = \frac{-\Delta A_X}{2L_0 \cdot \sin(\theta)} \quad (1)$$

where $\theta = |\theta_S|$, and ΔA_X is the difference between speckle shifts from beam 1 and beam 2

$$\Delta A_X = A_X(\theta_S) - A_X(-\theta_S). \quad (2)$$

The resolution of the technique, from Equation (1), is proportional to the minimum value of ΔA_X, or the minimum differential speckle shift, which can be measured. The minimum shift is generally taken to be the pixel pitch of the detector, although curve fitting can give a fractional improvement on the estimate of shift. Past systems have used values of $\Delta A_X = 15$ μm, $L_0 = 1$ m, and $\theta = 30°$ giving a resolution of about 15 $\mu\epsilon$. If high strain resolution is not needed, a more compact optical design can be achieved at the expense of strain resolution by reducing the value of L_0.

A design parameter to maintain, however, is the minimum pixel-to-speckle sampling ratio of the optical system.[4] This is the topic of the next section.

SPECKLE SAMPLING FREQUENCY

The pixel-to-speckle ratio (# of pixels per speckle = mean speckle diameter / pixel pitch) affects the accuracy of the cross-correlation. It is necessary to sample the speckle pattern below the resolution of the smallest speckle in order to make the most use of the correlation technique. It is also prudent not to greatly oversample the speckle pattern, because the overall number of samples that can be taken is limited by the elements in the detector. Film recording techniques have a minimum grain density requirement for the emulsion of the film; this electronic recording technique also has a minimum performance requirement. One advantage of this speckle correlation technique is that the recording media resolution requirement is relatively low; it is measured in tens of microns rather than tenths of microns as in holographic or other interferometric techniques.

By using an optimized sampling interval an attempt is made to record the most information possible about the intensity distribution of the speckle pattern. Having more than the optimum number of pixels / speckle does not increase the information content, or spatial frequency bandwidth, of the image. Rather, it decreases the information about the speckle distribution by limiting the number of speckles that will fit on the array, which is of finite length. The advantage of maximizing the information content is that if more information is read, the speckle pattern will look more unique in the correlation. This uniqueness of each particular window of the speckle pattern reduces the chance of ambiguous correlations.

A distinction is made between the *typical* speckle size, given by the width of the peak in the autocorrelation of a speckle pattern, and the *minimum* speckle size, which is inversely proportional to the highest spatial frequency generated by the optical system. The minimum speckle size is inversely related to the effective aperture of the optical system, which is a Gaussian aperture in this case. However, although the speckles change shape when using wire specimens with diameters smaller than the laser spot, the pixel-to-speckle ratio along the sensitive axis of the instrument remains unaffected. The analysis will be limited to the sensitive axis (the x component) of the optical system.

For a circular beam of non-normal incidence, one axis of the spot becomes elongated as shown in Figure 2. The parameter d, the spot diameter along the wire axis, is defined by the beam radius ω and incident angle θ_S:

$$d = \frac{2\omega}{\cos\theta_S}. \quad (3)$$

The angle θ_S along the wire axis is 30° in the current setup.

There exists joint normality between the uncorrelated random variables x and y,[5] implying that the marginal density of the x component is given by the Gaussian probability density

$$I(x) = I_0 \cdot e^{\frac{-1}{2}\left[\frac{x}{\sigma_x}\right]^2}. \quad (4)$$

This intensity is the square of the electric field. The laser spot diameter is related to the standard deviation σ_x by the relationship

$$d \equiv 4 \cdot \sigma_x. \quad (5)$$

The diffraction limited speckle radius r_X along the incident plane (parallel to the wire axis) can be calculated using the Fraunhofer approximation to the standard diffraction integral. The aperture function in the integral is a 1-D Gaussian function. The electric field of the "smallest speckle" in the sensor plane is given by

$$E(x) = A \int_{-\infty}^{\infty} e^{\frac{-x^2}{4\sigma_x^2}} \cdot e^{\frac{-ik}{2L_0}(x^2 - 2xx)} dx, \quad (6)$$

where the propagation vector $k \equiv 2\pi/\lambda$, λ is the laser wavelength, and L_0 is the specimen-to-sensor distance. The phase shift introduced by the non-zero incident angle is dropped. Solving Equation (6) gives

$$E(x) = B\, e^{-\left[\frac{\sigma_x k x}{L_0}\right]^2}. \quad (7)$$

The intensity I in the sensor plane is the square of the electric field, so

$$I(x) = C\, e^{-2\left[\frac{\sigma_x k x}{L_0}\right]^2}$$

$$= C\, e^{\frac{-x^2}{2\sigma_X^2}} \quad (8)$$

after defining

$$\sigma_X \equiv \frac{L_0}{2\sigma_x \cdot k} \quad (9)$$

to be the standard deviation of the Gaussian in the sensor plane.

The measure of a Gaussian function's radius is typically taken to be two standard deviations from the Gaussian's mean position when defined as in Equation (8). The radius r_X is thus defined to be at the e^{-2} point of Equation (8), noting that

$$r_X = 2 \cdot \sigma_X \implies \frac{r_X^2}{2\sigma_X^2} = 2. \quad (10)$$

Substituting Equation (9) into Equation (10) gives the radius of the intensity distribution of the "smallest" speckle:

$$r_x = \frac{L_0}{\sigma_x \cdot k}. \tag{11}$$

The optimum sampling frequency in the x direction is estimated to be the Nyquist sampling frequency, which is twice the highest spatial frequency present in any slice of the speckle pattern in the x direction. The spectral power density of the Gaussian is found by taking the Fourier transform of the exponential in Equation (8):

$$\mathcal{F}\left[e^{\frac{-x^2}{2\sigma_x^2}} \right] = \sqrt{2\pi}\, \sigma_x \cdot e^{-\frac{1}{2}(\sigma_x \kappa)^2} \tag{12}$$

The cut-off spatial frequency κ_c is again chosen to be the e^{-2} point, now of the Gaussian spectral power density. By equating the exponent in the right of Equation (12) to -2 and solving for κ_c,

$$\kappa_c = \frac{2}{\sigma_x}$$

$$= \frac{4\sigma_x \cdot k}{L_0}. \tag{13}$$

The Nyquist frequency

$$\kappa_N = 2 \cdot \kappa_c \tag{14}$$

then is proportional to the inverse of the optimum sampling interval a_N:

$$a_N = \frac{2\pi}{\kappa_N}$$

$$= \frac{\pi L_0}{4\sigma_x \cdot k}. \tag{15}$$

This gives a pixel-to-speckle ratio of

$$\frac{2 \cdot r_x}{a_N} = \frac{2 \cdot \left[\frac{L_0}{\sigma_x \cdot k}\right]}{\frac{\pi L_0}{4\sigma_x \cdot k}}$$

$$= \frac{8}{\pi} = 2.55 \left[\frac{\text{pixels}}{\text{speckle}}\right]. \tag{16}$$

To conclude, Equation (16) suggests that a sampling interval of 2.55 pixels per speckle diameter will avoid both oversampling and undersampling the speckle pattern. In practice, however, it is difficult not to oversample the speckle pattern due to system requirements for the strain measurement resolution, as defined in Equation (1). Generally, the minimum measurable strain occurs for $\Delta A_x = 1$ pixel. Using the Phase II pixel-to-speckle ratio calculation above as an example, it would be necessary to adjust L_0 to be 40.5 mm to give a sampling ratio of 2.55. This would reduce the strain resolution from 15 $\mu\epsilon$ to 370 $\mu\epsilon$ – a significant compromise. In addition, it is often impractical to adjust the speckle size by varying the spot diameter on the specimen, because the spot size determines the gage length of the measurement.

ROOM TEMPERATURE TESTS

When using a specimen of small thermal mass it is important not to induce local heating by the laser beam. This kind of heating causes thermal strain at the gage location, which contributes to speckle shifts. Since the shifts are due to real strain, they cannot be cancelled; they will consequently degrade any stress-strain relationship being measured. It is, of course, undesirable for the instrument to affect the measurement in any way.

During the room temperature tests for this study, thermal strain was observed to be a problem at high laser power density levels. Once the laser output power was reduced from 2 W to $1/2$ W, the stability of the speckle patterns over successive exposures increased. For an incident power of 0.5 W and a 30 ms exposure time, the speckle patterns varied between a shift of zero and one diode over a series of twenty exposures (about 20 minutes duration). Thermal strains were, therefore, negligible. The correlation function was sharply peaked over the duration of the test. Tungsten and stainless steel wires with diameters of 76 and 813 μm (3 and 32 mils), respectively, were used for these tests.

Correlations were also performed on speckle patterns from a variety of unloaded ceramic fiber specimens. The lower reflectivity of the ceramic fibers reduced the signal-to-noise level compared to the metallic specimens. However, these signals can be improved with a more sensitive sensor.

HIGH TEMPERATURE TESTS

One of the critical questions associated with high temperature optical measurements is whether thermal density gradients during a test are severe enough to prohibit accurate readings. Past testing has indicated problems of this sort at temperatures as low as 450°C. Free convection set up by air temperature/density variations around a hot specimen can result in an unstable phase propagation medium for the speckle-forming laser light. Since a stable speckle pattern depends explicitly on stable phase relationships, dynamic density variations can severely degrade the measurements. Image shifting due to refractive index gradients is described in more detail in the literature.[6]

If the density variations occur within a spatial extent smaller than a cross-section of the solid angle subtended between the laser spot on the specimen and the speckle pattern on the sensor, the speckle pattern will exhibit a boiling action. If, on the other hand, the phase medium varies on a scale larger than the cross-section of this solid angle the speckle pattern will jitter or vibrate as a field at the sensor. The latter case was observed during early testing.[2] In later testing[3] the specimen was enclosed in a thermally insulating box. Subsequently, the jitter effect was not observed at test temperatures beyond 750°C.

Thermal effects of the first kind (boiling) cannot be compensated for if they exceed some minimum criterion necessary to maintain correlation between exposures. However, the situation is different for speckle shifts due to thermal variations of the second kind, ie. those on a scale larger than the aforementioned solid angle. These shifts can be cancelled as rigid body motions *if* the shifted speckle pattern pair (one exposure from each beam) can be acquired fast enough to stop the relative movement of the thermal zone between exposures.

Further experiments were necessary to determine if the problem would recur at the much higher temperatures desired for future materials testing. An ac light bulb was used to provide a very hot wire specimen. The bulb provided a means of testing a tungsten alloy in an inert atmosphere using standard hardware. The glass envelope sealed the wire filament in dry nitrogen gas to prevent oxidation of the tungsten. The operating pressure in the envelope was estimated to be ≈1.5 atm. The envelope was transparent and cylindrical in shape (measuring 9 cm long by 3 cm in diameter), allowing the necessary optical access for the laser beams and speckle patterns. A variac was used to adjust the voltage across the filament without clipping the ac signal, effectively varying the filament temperature. A calibration of temperature versus line voltage was obtained from the bulb manufacturer.

The filament was made from a 37 μm (1.5 mil) diameter wire of W-Re alloy. The wire was tightly wound into a 122 μm (4.8 mil) diameter filament. It has been observed in high temperature testing of the speckle-shift technique that speckle pattern movements can stem from three sources:

1) Strain along the sensitive axis of the gage;

2) Rigid body motions of the specimen, including rotations and translations, caused by either mechanical or thermal sources (a change in temperature anywhere along the specimen can translate the test section through thermal strain);

3) Instabilities of the phase propagation medium between the specimen and sensor.

Using the bulb's filament as a specimen had the fortuitous advantage of separating speckle movement source 3) from sources 1) and 2). It is believed that the coiled filament absorbed any thermal strains in the coils, which tended to inhibit translations of the bulk filament. This made it possible to isolate the test from all effects except those of the propagation medium. The speckle statistics accurately obeyed those of a 122 μm diameter solid wire. A series of speckle patterns were recorded and correlated with a single pair of reference patterns at a specimen temperature of 2,480°C. Excellent stability was observed in the high temperature tests, indicating that the isolation provided by the glass envelope was sufficient to avoid thermally induced jitter. The correlation peak occurred at shift values of 0 and 1 pixels over time, which is within the resolution of the correlation algorithm. Figures 3.a and 3.b show a set of reference and shifted speckle patterns, and their correlation over a shift range of ±60 pixels. The patterns were recorded using a linear photodiode array camera. Since the wire was subjected to neither load nor rigid body motion, there should be no offset between the patterns. Indeed, the correlation in Figure 3.b is sharply peaked at an offset of zero, as expected. The speckle pattern stability was also very good at room temperature and 1,825°C.

It is important to note that these results alone do not guarantee accurate measurements at high temperatures using a straight wire specimen. Acquisition of the speckle pattern pairs must always occur fast enough to stop the action of any translations of the specimen or changes in the strain state at the gage position introduced by the test apparatus.

ADVANCED SYSTEM REQUIREMENTS

The Advanced System effort will concentrate on developing a one-dimensional strain measurement system capable of calculating strains using a high speed digital signal processor (DSP). The system will provide the abilities to continuously track on-axis and off-axis speckle movements from a stressed wire specimen, and measure the induced strain. The ability to track the reference speckle patterns when off-axis speckle movements occur diminishes decorrelation effects and increases the measurement range of the instrument. In addition, the alignment criteria for the test specimen will not be as stringent, and less specialized load apparatus can be used for the tests.

Full field speckle patterns will be recorded electronically by the system as the specimen undergoes strain and rigid body motions. When the speckle pattern shifts off the primary viewing axis during a run, the reference slice (the center video line of the unshifted speckle pattern) will still be somewhere on the two-dimensional sensor array and correlation can be maintained. However, the processing speed of the system will need to increase to meet the demands of this improvement. It will be necessary to perform a number of correlations per strain point to track the speckle shifts. The reference speckle patterns must be correlated with video lines on the array both above and below the reference axis coordinate. This is essentially a two-dimensional correlation over a narrow, automatically selected range. The speckle tracking algorithm will search for a correlation peak in each video frame until some minimum confidence criterion is met. The coordinates of this correlation peak give the shift components along the sensitive strain axis as well as the transverse axis. In addition to finding the coordinates of the correlation peak, the DSP-based image processor will automatically update the reference patterns before decorrelation occurs, allowing a virtually unlimited range of strain and rigid body motion shifts.

HARDWARE

The optical system will be a switched single beam design, for compactness, following the schematic in Figure 4. The argon ion laser beam can be diverted into the beam stop by the acousto-optic modulator (AOM) between tests and exposures. The Pockels cell and polarizing beamsplitter form an optical switch, in order to provide two beam paths for error cancellation. The Pockels cell can rotate the polarization of the beam by $\pi/2$ radians in accordance with a control signal. This allows the beam to either pass through the polarizing beamsplitter (beam leg 1) or be reflected to beam leg 2. A waist positioning achromatic lens is used to provide a planar wavefront at the specimen surface.

The data acquisition system is based on a high performance personal computer. This PC is the system controller, synchronizing the video and load data acquisition with the strain calculations. Figure 5 shows a block representation of the system control paths. The video frame grabber and DSP card plug into the computer's 16 bit I/O bus. The controller executes custom programs optimized to perform various overhead operations, while the frame grabber acquires the speckle image data from the CCD camera controller and the DSP correlates the images. A programmable function generator switches the Pockels cell in synchronization with the camera. This synchronization is achieved with a custom logic signal indicating the CCDs' refresh timing. The signal triggers the function generator, which in turn toggles the state of the Pockels cell. The function generator can send and receive configuration information over the IEEE-488 bus (GPIB). Also on the GPIB is a digital I/O unit, and an analog-to-digital (A/D) converter. The digital I/O unit controls the state of the acousto-optic modulator by turning on or off the RF signal to the crystal. The A/D converter digitizes the voltage across a load cell connected to the specimen mount.

CONCLUSIONS

Preliminary high temperature testing showed that stable objective speckle patterns can be recorded from a tungsten filament at 2,480°C. The gas immediately surrounding the filament was enclosed by a thin glass envelope.

A high speed strain measurement system is discussed, which will be able to track moving speckle patterns in two dimensions. This high speed tracking ability allows the speckle-shift technique to be used in more diverse test environments. The performance is achieved by using a plug-in digital signal processor card in an AT-class computer.

An analysis of the minimum sampling frequency of the speckle pattern is given. The analysis helps the designer of a speckle-shift system to stay within bounds of the optical requirements of the technique when design parameters are varied to suit the test.

REFERENCES

1. Yamaguchi, I.: A Laser-Speckle Strain Gauge. J. Phys. E. Sci. Instrum., vol. 14, no. 11, Nov. 1981, pp. 1270-1273.

2. Lant, C.T., Qaqish, W.: Optical Strain Measurement System Development - Phase I. Sverdrup Technology, Inc., NASA Contract NAS3-24105, NASA CR-179619, 1987.

3. Lant, C.T.: Two-dimensional High Temperature Optical Strain Measurement System - Phase II. Sverdrup Technology, Inc., NASA Contract NAS3-25266, NASA CR-185116, 1989.

4. Lant, C.T.: Feasibility Study for the Advanced One-Dimensional High Temperature Optical Strain Measurement System - Phase III. Sverdrup Technology, Inc., NASA Contract NAS3-25266, NASA CR-185254, 1990.

5. Papoulis, A.: Probability, Random Variables, and Stochastic Processes. 2nd ed., McGraw-Hill, 1984, pp. 125-127.

6. Stetson, K.A.: The Use of Heterodyne Speckle Photogrammetry to Measure High-Temperature Strain Distributions. Holographic Data Nondestructive Testing (A84-28618 12-35), SPIE - The International Society for Optical Engineering, Bellingham, WA, 1983, pp. 46-55.

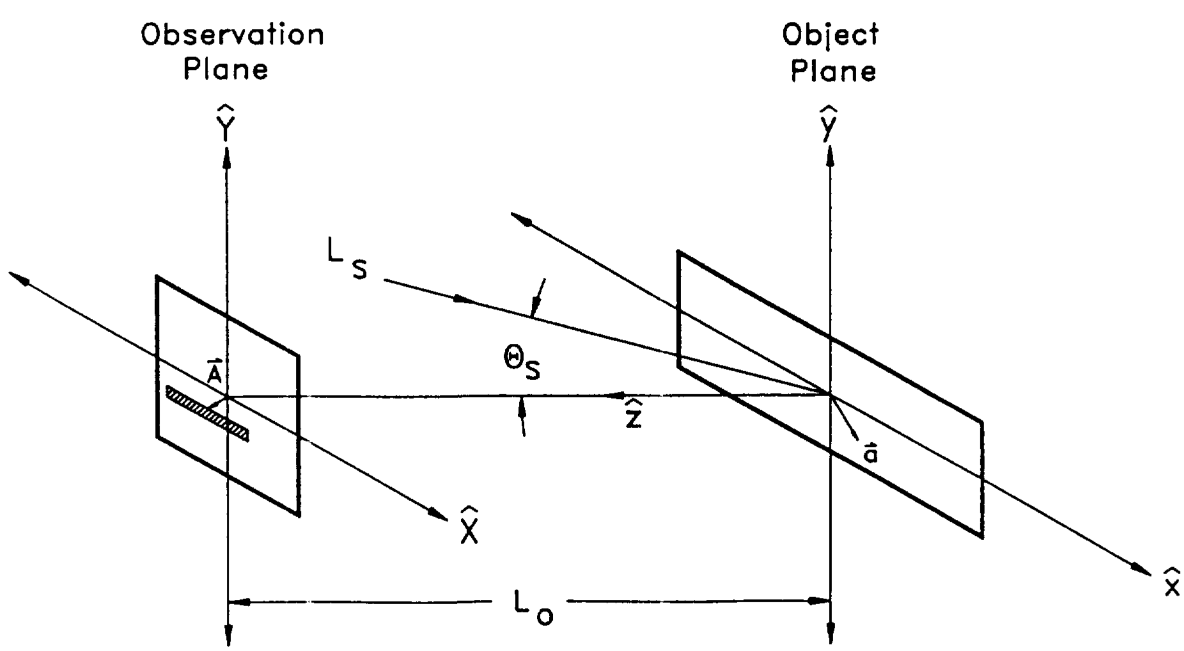

Figure 1. - Simplified coordinate system.

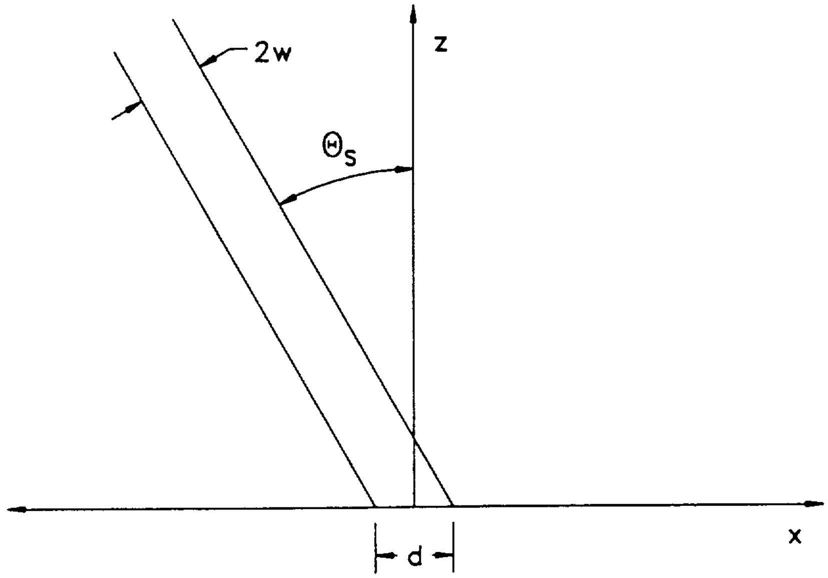

Figure 2. - Beam elongation.

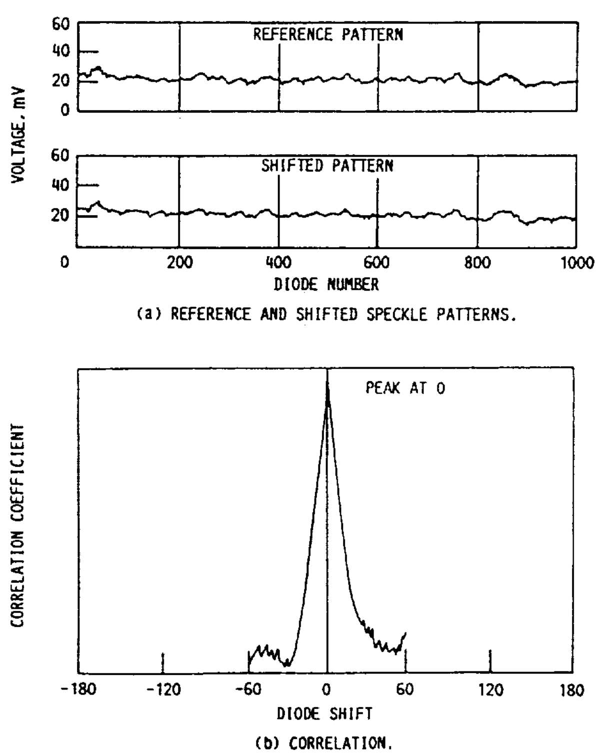

Figure 3. - Typical speckle pattern pair and their, correlation, for a tungsten wire at 2,480 °C.

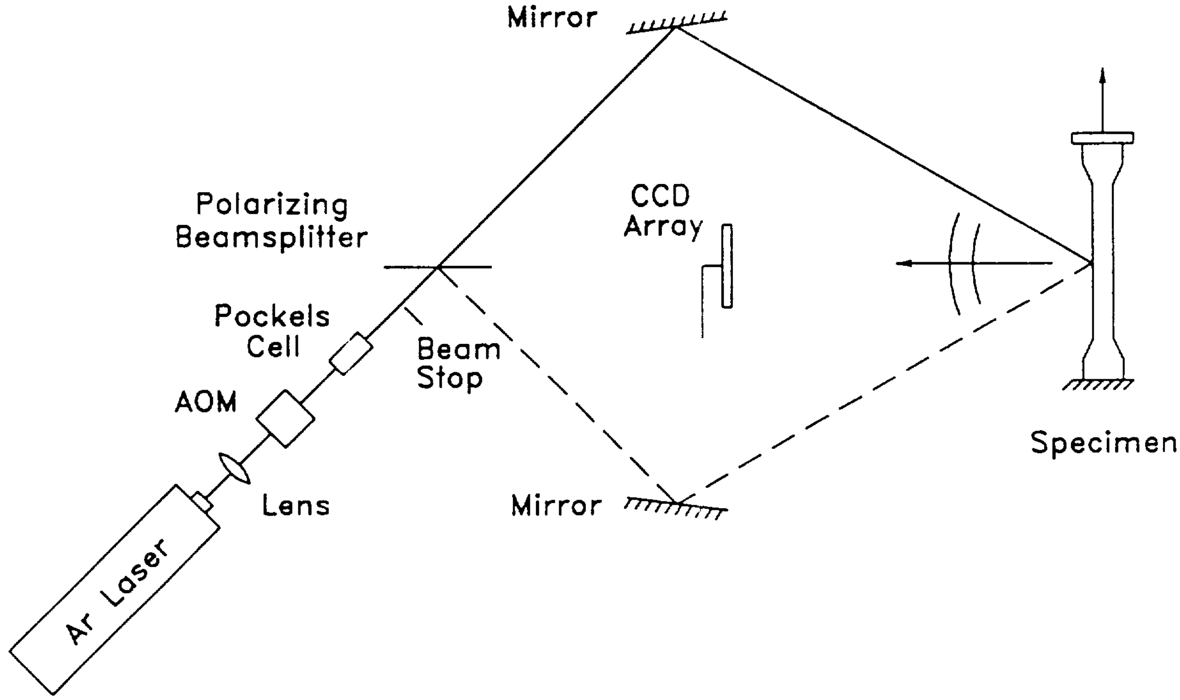

Figure 4. - Optical schematic.

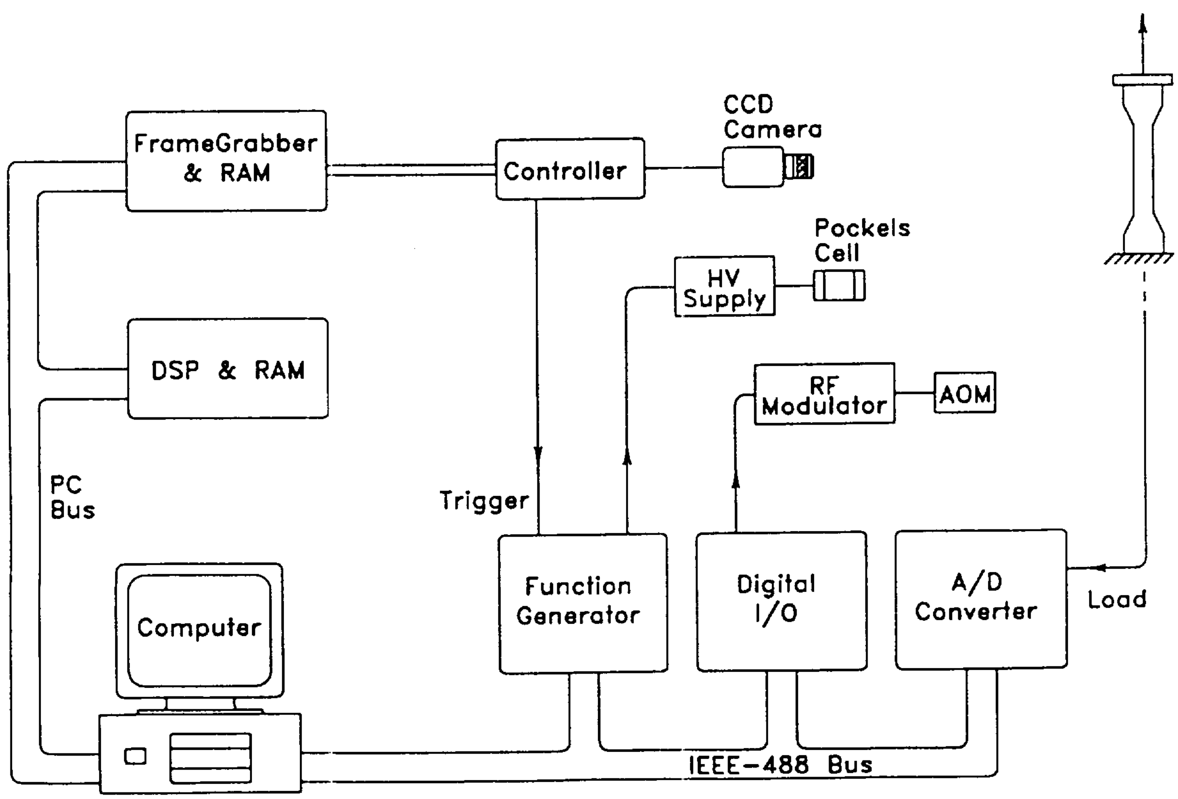

Figure 5. - Block diagram of Advanced System.

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16. Abstract

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